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Applying NeuroIS to Chronic Pain: Using Heatmaps to Understand Contextual Factors

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ABSTRACT

Advances in science have significantly enhanced our understanding of information-processing behavior. This paper uses fixation duration and pupil size heatmaps to examine differences in attention and arousal between individuals with and without chronic pain as they complete a series of pain-related surveys commonly used in clinical settings. This study provides insight for designing intelligent tools to detect chronic pain via eye movements. While existing research has mainly focused on attentional biases towards pain-related stimuli, our study highlights the importance of considering emotional responses reflected in ocular behavior. Moreover, because attention and emotional responses are sensitive to the content and presentation of stimuli, visualizing these processes as heatmaps offers a deeper understanding of how information is processed. This can significantly aid in developing advanced systems that detect human experience, such as chronic pain, based on eye movement patterns.

Keywords

Eye tracking, chronic pain, attentional bias, pupillometry, neuro-IS, heatmaps

INTRODUCTION

NeuroIS, an interdisciplinary field that merges neuroscience with information systems (IS), utilizes neurophysiological tools and measures to enhance behavior detection and user experience within IS contexts (Bačić and Henry, 2022; Loos, Minas, Ogawa and Crosby, 2021). By leveraging technologies like eye-tracking, NeuroIS offers detailed moment-to-moment data, useful in understanding complex, subjective experiences such as chronic pain. Chronic pain, defined as pain lasting for more than three months (Merskey, 1986), significantly impacts patients' quality of life (Hadi, McHugh and Closs, 2019). Chronic pain is currently evaluated through self-reports, but this subjective approach can be enhanced by integrating objective biomarkers like visual attention (Alrefaei, Djamasbi and Strong, 2023) and arousal. Pain impacts visual attention (Alrefaei, Sankar, Norouzi Nia, Djamasbi and Strong, 2022; Fashler and Katz, 2016; Gaffeiro, Elander and Maratos, 2019), making eye-tracking a valuable tool in developing Clinical Decision Support Systems (CDSS) for chronic pain detection (Alrefaei et al., 2023; Riedl, Fischer, Léger and Davis, 2020). This study leverages heatmaps representing sustained attention and arousal to distinguish differences in ocular behavior between individuals with and without chronic pain, capturing patterns that traditional fixation-based studies may miss (Chan, Suen, Jackson, Vlaeyen and Barry, 2022). Since chronic pain often elicits emotional responses like fear and anxiety (Elman and Borsook, 2018), visualizing these responses through heatmaps can enhance clinicians' understanding of both cognitive and emotional dimensions' of their patients' pain experiences.

BACKGROUND

According to pain literature, individuals suffering from chronic pain tend to exhibit a greater degree of selective attention toward pain-related information (Phelps, Navratilova and Porreca, 2021; Todd, Sharpe, Johnson, Perry, Colagiuri and Dear, 2015). A systematic literature review (SLR) shows that the impact of pain on attention can be effectively measured by capturing sustained attention, which can be quantified with fixation duration (FD) (Chan et al., 2020). While FD patterns can reveal which visual components elicit sustained attention (Djamasbi, Siegel and Tullis, 2010; Djamasbi, Siegel, Skorinko and Tullis, 2011), little work has been done to examine differences in these patterns between people with and without chronic pain (Chan et al., 2020). Selective attention to pain-related information among individuals with chronic pain is often driven by their difficulty in suppressing painful memories (Phelps et al., 2021; Todd et al., 2015). Also, while it is well-established that pain evokes emotional responses (Aaron, Mun, McGill, Finan and Campbell, 2022), existing pain literature has not thoroughly examined the differences in emotional responses between individuals with and without chronic pain when processing pain-related information (Chan et al., 2020). Emotional responses to pain can be effectively measured using pupil size, which provides a noninvasive method to assess the autonomic nervous system (ANS) response to pain (Connelly, Brown, Kearns, Anderson, St Peter and Neville, 2014; Kruglov and McGuckin, 2023). Both the sympathetic and parasympathetic branches of the ANS (Beatty and Lucero-Wagoner, 2000; Höfle, Kenntner-Mabiala, Pauli and Alpers, 2008) involved in pupil size changes are involved in managing emotions related to chronic pain as well (Ziadni, You, Johnson, Lumley and Darnall, 2020). In this study, we use FD and pupil size heatmaps to explore differences in attentional and arousal patterns elicited by pain-related stimuli (Chen, Kuo, Hsu and Wang, 2022; van Steenbergen, Band and Hommel, 2011) between individuals with and without chronic pain. Such a comprehensive understanding can help to advance research that focuses on developing intelligent systems capable of detecting chronic pain based on eye movement patterns.

METHODOLOGY

To investigate the viewing patterns of individuals with and without chronic pain, we used visual stimuli from a previous NeuroIS study that examined differences in information processing behavior between these two groups (Alrefaei et al., 2023). These stimuli included pain-related measures from the Patient-Reported Outcomes Measurement Information System (PROMIS) 29+ v2 profile, which was developed by the National Institutes of Health (NIH). For this IRB-approved study, participants were recruited from students at a university in northeast US. Participants' eye movements were recorded as they completed the PROMIS 29+ v2 profile. Participants were asked to self-identify their chronic pain status before the experiment which was again verified after the experiment as well. They were provided with a definition of chronic pain, described as intense pain (a rating of 4 or higher on a 1-10 scale) lasting at least three months. Participants were then asked to classify themselves as either having chronic pain, being pain-free, or being somewhere in between. This information was subsequently used to categorize the eye movement data for creating the heatmaps. Eye movements were collected using a Tobii Pro Spectrum eye-tracker with a 600Hz sampling rate, built into a 23.8-inch monitor with a 1920*1080 resolution. The raw gaze data from participants was processed through the Identification by Velocity Threshold (IVT) filter, part of the Tobii Pro Lab software, version 1.162 (64-bit Windows). We set the velocity threshold at 30 degrees per second and defined the minimum duration for detected fixations at 100 milliseconds (Liu, Trapp and Djamasbi, 2021). Participants' data was extracted for analysis and the dataset for each participant was filtered for the eye movement type concerning fixations. The preliminary analysis reported in this study was conducted using the initial data collected for the larger project to which this study belongs. Since our focus was on comparing differences in fixation and pupillary response patterns between people with and without chronic pain, for our preliminary analysis we aimed for an adequate sample size in each group. Once we had collected data from 11 participants in each group, we began our analysis, ensuring a representative and sufficient dataset for meaningful comparison of the heatmaps (Djamasbi, Siegel and Tullis, 2012).

Developing heatmaps

Fixation duration (FD) and pupil dilation (PD) are both metrics used in eye-tracking research to understand visual attention and cognitive processing. FD, expressed in milliseconds (ms) represents attentional maintenance or the amount of time for which the eye maintains its gaze on a specific element or area of interest (AOI) within the visual field. PD, expressed in millimeters (mm) refers to the average pupil size of both eyes. PD serves as a quantitative indicator for various physiological and psychological processes, such as arousal, cognitive load, emotional response, and neurological activity (Aston-Jones and Cohen, 2005; Jerčić, Sennersten and Lindley, 2020; Maier and Grueschow, 2021; Nilsson, Bärgman, Ljung Aust, Matthew and Svanberg, 2022). The pupil data for heatmaps were prepared with baseline correction method which involves adjusting the pupil signal using data collected during a designated baseline period (Fink, Simola, Tavano, Lange, Wallot and Laeng, 2023). We adopted the subtraction method for baseline correction (Laeng and Alnaes, 2019; Mathôt, Fabius, Van Heusden and Van der Stigchel, 2018). The baseline-corrected values represented pupil sizes relative to the baseline, with negative values indicating constriction, positive values indicating dilation, and a value of 0 indicating no change. Because pupil dilation is an indicator of arousal (Mathôt and Vilotijević, 2022; Unsworth and Robison, 2014) we used only the positive baseline-corrected values to develop the pupil size heatmaps. The collected dataset included x and y gaze point coordinates to overlay the gaze data on its respective visual stimuli. Since we did not have a time limit for the task in our study we normalized the fixation durations. To do so, for each participant, we summed the duration for every unique set of coordinates and divided these summed data points by the total fixation duration of the participant. Similarly, for each participant, the mean baseline-corrected pupil size at each unique set of coordinates was normalized by dividing it by the participant's total fixation duration. Since the eye movement metrics in both heatmaps were normalized using the ratio of total fixation duration, these heatmaps allowed us to compare the levels of sustained attention and arousal elicited by the visual stimuli content. We organized the datasets based on participants self-identification of their chronic pain status, i.e. chronic pain (CP), and pain free (PF) groups. We then aggregated the normalized data for each eye movement metric (FD and PD) across participants for every unique set of coordinates. Heatmaps were generated for each group by mapping the metrics along with the coordinates. The highest values were represented with the warmest color, in our case, red. To ensure that the color mapping was of some biological importance, we calculated the weight distribution based on distance from the fixation point using the cubic Hermite spline function (cspline) as outlined in the Tobii Pro Lab manual (Tobii Pro AB, 2014). While this ensured that each data point contributed to the heatmap with a certain degree of smoothness, the data could still have some abrupt transitions or uneven distributions. So, we applied the Gaussian filter to smooth the entire heatmap (Courtemanche, Léger and Dufresne, 2017; Holmqvist, Nyström, Andersson, Dewhurst, Jarodzka and Van de Weijer, 2011). This helped to spread out the values, reduce noise, and create a more visually appealing heatmap. Moreover, having an equal number of participants in both groups facilitated the fair comparison of heatmaps. The same color scale range was assigned to both groups decided by the highest value of the concerned metric across both groups. This ensured that the intensity of colors represented the same level of intensity in both heatmaps.

PRELIMINARY RESULTS

Figures 1-3 display the fixation duration (FD) and pupil size (PD) heatmaps for both groups of participants across three types of pain-related visual stimuli: physical function, pain interference, and pain intensity. Because heatmap patterns are generated based on the locations of fixation points on the visual stimuli, the dispersion of visual patterns for FD and PD is consistent within the same group of participants. More red and yellow clusters, along with darker shades of red, yellow, and green, suggest higher levels of sustained attention to the provided information (Djamasbi, 2014; Djamasbi et al., 2010). The dispersed fixation patterns covering survey questions show thorough reading behavior for both groups (Alrefaei et al., 2022). However, the slightly denser and more intense color clusters on the heatmaps for the pain free group show that this group exhibited more sustained attention than chronic pain group when reading the questions. The fixation patterns in the answer area show that participants in both groups exhibited more focused attention when they were responding to survey questions compared to when they were reading the questions. However, the two groups differed in where they focused their attention when they were deciding which option to select. For example, heatmaps for physical function and pain interference stimuli shows that pain free participants sustained their attention longer on the first two labels while chronic pain participants examined the first four labels with longer fixations. When rating their pain intensity experience, pain free participants examined the labels and the first option with longer fixations. Chronic pain participants examined only one of the labels and examined options 4, 5, and 6 with the most intense fixations. The pupil size heatmaps show the levels of arousal for the stimuli components examined by the participants. These heatmaps show higher arousal levels in the pain-free group compared to the chronic pain group when completing the pain interference and physical function surveys. In the pain-free group, both the question and the answer areas of these two visual stimuli tend to elicit similar arousal levels. In contrast, arousal levels were higher in the answer area for the chronic pain group. The differences in arousal levels between the two groups for the pain intensity stimulus contrasted with those observed for the physical function and pain interference stimuli. Unlike the other two stimuli, arousal levels were higher in the chronic pain group when completing the pain intensity survey, especially when examining options 5, 6, and 8, which triggered more intense arousal. In contrast, the pain-free group showed higher arousal levels when focusing on the labels of this visual stimulus.

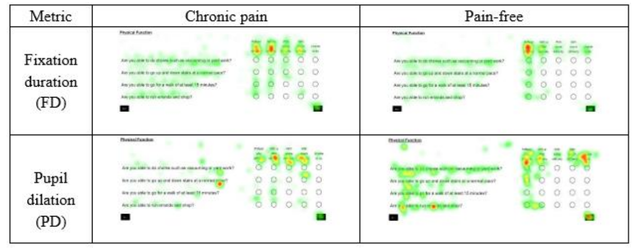

Figure 1. Heatmaps for the physical function stimulus

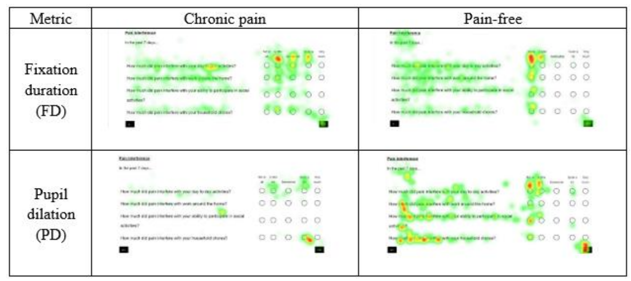

Figure 2. Heatmaps for the pain interference stimulus

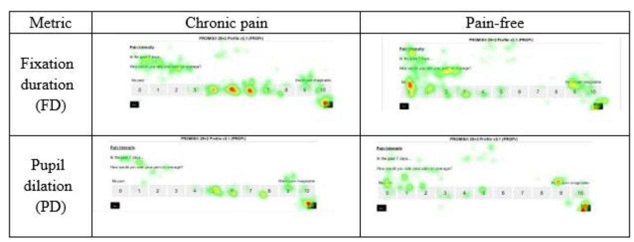

Figure 3. Heatmaps for the pain intensity stimulus

DISCUSSION

The heatmaps showed that both groups demonstrated more intense fixation patterns in the answer areas than in the question areas, reflecting the difference between cognitive activities involved in reading versus decision-making. However, the two groups differed in their focus areas when making decisions. For example, pain-free participants primarily focused on the first two labels, while participants with chronic pain examined the first four labels when selecting options for the physical function and pain interference measures. In deciding on pain intensity, pain-free participants paid close attention to the labels, whereas chronic pain participants focused primarily on the most severe label and options representing moderate pain levels (options 4, 5, and 6). Overall, the heatmaps depicted that the chronic pain group paid less attention to the questions than the pain free group. Paying less attention to the questions by chronic pain group is consistent with studies that show attentional bias toward pain-related stimuli can manifest as decreased vigilance or avoidance of painful stimuli (Chan et al., 2020; Fashler and Katz, 2014, 2016; Gaffeiro et al., 2019; Vervoort, Trost, Prkachin and Mueller, 2013). In our study, the heatmaps indicate that participants with chronic pain may have employed such avoidance strategies to escape the negative feelings invoked by pain related questions (Eccleston and Crombez, 1999). The results also showed that the chronic pain group exhibited lower arousal levels than the pain-free group when completing the physical function and pain interference surveys. Individuals with chronic pain displayed higher arousal levels when answering questions than when reading them. By becoming more emotionally engaged in the task of selecting choices, they may have employed an avoidance strategy to escape the painful feelings and memories triggered by the questions (Eccleston and Crombez, 1999). When selecting options on the pain intensity survey, which asked them to rate their pain experience, participants in the chronic pain group showed higher arousal levels than those in the pain-free group. This could be because they had to think about their pain to answer this question. These findings support our expectation that spatial visualization of sustained attention and arousal can provide valuable insights into differences in information processing between people with and without chronic pain.

LIMITATIONS AND FUTURE WORK

While our results provide valuable insights into differences in information processing patterns between chronic pain and pain-free participants using normalized fixation duration and baseline corrected pupil dilation, we aim to replicate this study with a larger sample size to enhance generalizability. Additionally, generating heatmaps for other fixation and pupil-based metrics could offer deeper insights into the cognitive processes affected by chronic pain. Exploring how these heatmaps can be applied to other IS phenomena, such as user engagement or decision-making in contexts other than pain, presents a promising avenue for future research.

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